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Quantitative Interpretation of Geomagnetic Induction Response Across the Thrust Zones of the Himalaya along the Ganga-Yamuna Valley

C. D. REDDY and B. R. ARORA

Indian Institute of Geomagnetism, Colaba, Bombay 400005, India

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Geomagnetic variations, recorded through a two-phase magnetovariational study carried out along the Ganga-Yamuna valley of the Garhwal Himalaya, northwest India, are reduced to a set of induction arrows spanning a period range of 12–128 minutes. The spatial behaviour of induction response indicates that the Main Frontal Thrust is a major electrical discontinuity with enhanced conductivity to the south, beneath the Indo-Gangetic plains. Simple two-dimensional (2-D) geoelectrical models with geophysical constraints on the thickness and resistivity of the sedimentary sequences indicate that the induced currents in the Indo-Gangetic plains contribute little to the observed induction response.

A full 2-D electrical resistivity model which reproduces the observed electromagnetic response, essentially requires a highly conducting layer at mid-crustal depth beneath the Indo-Gangetic Plains, becoming less conducting on underthrusting beneath the frontal Himalayan belt. This layer coincides with the brittle-to-ductile transition zone along which lie the foci of most moderate earthquakes.

1. Introduction

Himalaya is a major geodynamic system with subduction zones, intrusions, mega fractures, faults and folds. It is well accepted that the Himalaya came to its existence out of collision between Indian and Eurasian Plates and subsequent underthrusting of the Indian lithosphere beneath the Eurasian plate. Spatial distribution of hypocentres and mechanism associated with medium sized earthquakes support the collision model for the Himalayan orogeny. Based on available geological and geophysical data, LEFORT (1975), POWELL (1979), SEEBER *et al.* (1981), BURG and CHEN (1984) and NI and BARAZANGI (1984) have proposed different plate tectonic models of the Himalaya. Despite the continuous growth of geological and geophysical data, the evolution of the Himalaya is not yet completely understood and the picture of sub-surface structures remains elusive. Electromagnetic (EM) geophysics is a powerful tool to explore internal structure of the Himalaya collision zone, for the following reasons:

1. the sizes of various litho-tectonic units of the Himalaya fall within the skin-depth range of EM induction and
2. the frequency dependence and independent estimation of real and quadrature components of response functions provide finer constraints on conductivity models.

To investigate the sub-surface structures of the Himalaya and contiguous Indian shield, in terms of electrical conductivity, first magnetovariational study in the form of a regional-scale magnetometer array was carried out during 1979 over NW India, encompassing in part the frontal belts of the Himalaya (LILLEY *et al.*, 1981). This array in addition to delineating a major conductive structure striking across the Himalaya (subsequently referred to as Trans-Himalayan Conductor—THC) proved effective as a reconnaissance study of geomagnetic induction patterns reflecting electrical conductivity structure in the northwest India (ARORA *et al.*, 1982). In subsequent years, couple of closely spaced linear profiles of magnetometer were operated to supplement

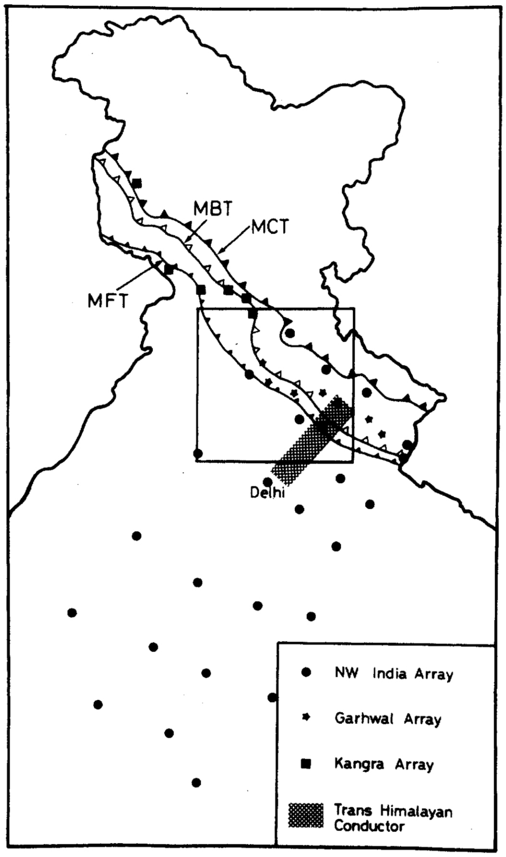

Fig. 1. Map of NW India showing the locations of the magnetometer arrays operated till 1985. Position of the mapped Trans-Himalayan Conductor is also shown. Rectangular block marks the location of the present study area, shown in expanded form in Fig. 2.

data on the THC (ARORA and MAHASHABDE, 1987) and on the electrical discontinuity aligned with the foothills of the Himalaya (MAHASHABDE *et al.*, 1989). Figure 1 gives the location of arrays operated till 1985 in NW India vis-a-vis the position of the THC. In our continuing efforts to understand the geoelectric configuration of the complex Himalayan zone, two more profiles of magnetometers have been carried out during 1987 and 1990 along the tectonically active Ganga-Yamuna Valley of the Garhwal Himalaya. Figure 2 gives the layout of the magnetometer sites occupied in these surveys. The extended geographical coverage was obtained by two independent field operations. The profile covered in phase-I was intended to provide magnetometer coverage along a section of the Main Central Thrust, which has been seismically active in recent years (GAUR *et al.*, 1985). The field recordings on this profile was carried out during November–December, 1987 and study area witnessed a destructive earthquake on October 20, 1991 with its epicenter close to Uttarkashi. The preliminary results of this study, particularly with reference to the Uttarkashi earthquake has been discussed by REDDY and AROR (1992a, 1992b). The second profile operated during 1990, provided coverage across the three major lithotectonic boundaries of the Himalaya and Indo-Gangetic Plains (IGP) and was specially designed to pick up the EM induction response relatively free from the influence of the THC. To summarize the signatures of

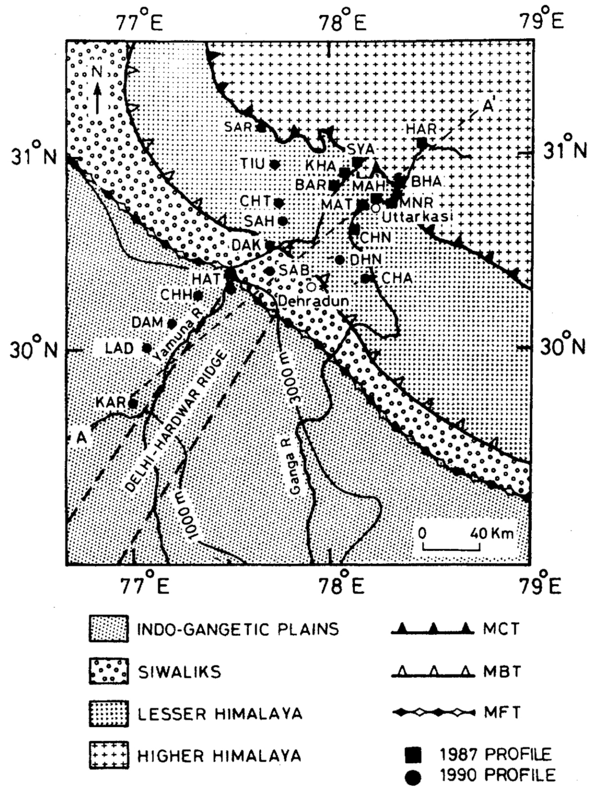

Fig. 2. Distribution of magnetometer sites across the thrust zones for a block of Himalaya whose location is shown in Fig. 1. Line AA' marks the profile referred to in Figs. 4–6.

EM induction, revealed by these profiles of magnetometer, a 2-D electrical resistivity model has been developed and its tectonic significance highlighted in the present paper.

2. Layout of the Magnetometers

The present study is mostly confined to the Ganga-Yamuna Valley, encompassing different terrains of the Himalaya; the IGP, Siwaliks, Lesser Himalaya and Higher Himalaya. These terrains are separated respectively by major thrusts; Main Frontal Thrust (MFT) or Himalaya Frontal Thrust (HFT), Main Boundary Thrust (MBT) and Main Central ("Vaikrita") Thrust (MCT). Magnetometer sites were uniformly distributed along these tectonic units (Fig. 2). Sites occupied during the first phase are primarily centered around MCT which characterizes the zone of intense shearing and dips 30–45° northwards. Six of the sites, HAR, BHA, MNR, MAH, MAT, and CHN, are laid along the track of the Ganga river (eastern line), whereas the sites SYA, KHA and BAR, lie along the Yamuna river (central line).

In the second phase, ten magnetometers were operated at SAR, TIU, CHT, SAH, DAK, HAT, CHH, DAM, LAD and KAR located along the Yamuna river. This profile provided coverage across the MBT and MFT and extends well into the IGP. Discussing the structural configuration of these thrusts along this sector, SAKLANI and BAHUGUNA (1986) visualized the MBT as a low angle thrust, which dips north by 20–25°, with gradual decrease in dip with depth. The MFT, which underlies the Himalaya, is an echelon series of steep faults and cuts obliquely the Siwaliks.

3. Analysis of the Data

About fifteen disturbance events from each phase of recordings were selected containing variations with wide frequency content and maximum possible range of polarizations for stable estimations of transfer function (GOUGH and DE BEER, 1980). Ideally, the variations recorded at the permanent observatory Sabhawala (SAB) could be used to compute inter-station type of transfer functions which would ensure linkage and homogeneity between two successive field operations. However, the horizontal field components at SAB are found to contain a substantial anomalous field determined by the effect of current channelling (unpublished results of the authors). In the present work, single-station type of transfer functions for ten period bands, spanning 16–128 minutes have been computed for each site. Transfer functions which are complex and frequency dependent exist in such a manner that, at a given frequency for the given site, they relate normal and anomalous fields in a unique way. The transfer functions are computed using the spectral formulation approach of SCHMUCKER (1970). Real (in-phase) and quadrature (out-of-phase) induction arrows which point towards the region of high conductivity (PARKINSON, 1959), are obtained using the transfer functions, and are shown in Fig. 3 for periods of 39 and 60 minutes.

The spatial variation in the magnitude of real and quadrature parts of the induction arrows is shown in Fig. 6, together with the error bars of 1 standard deviation. In general, errors are appreciably large. In the Himalayan terrains, which are relatively less habitated and industrialized, the level of the man-made electromagnetic noise is expected to be small. The large errors may arise due to the following factors:

1. Due to limited periods of recordings and low level of magnetic activity, events (sometimes even weak ones) were selected from both day- and night-time. External source field contri-

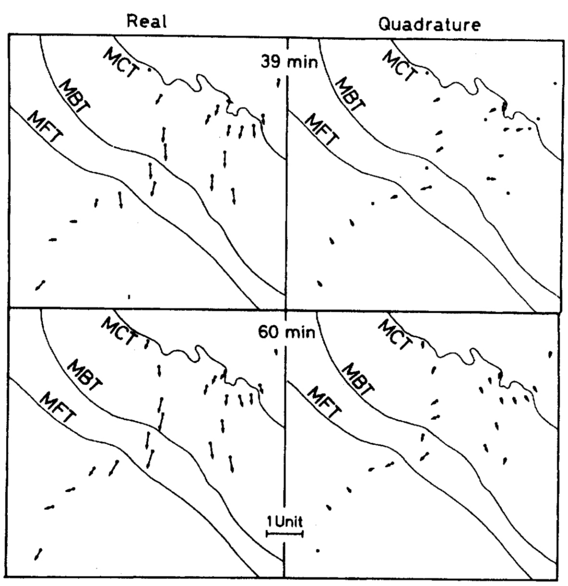

Fig. 3. Real and quadrature arrows for periods 39 and 60 minutes.

butions to Z variations, due to varying degree of spatial uniformity between day and night events, would serve as noise in the statistical estimation of transfer functions.

2. The most simple evaluation and interpretation of induction arrows follows when they are caused by simple 2-D structures. In a 3-D situation or in a multi-conductor environment the nature of resulting arrows at individual sites would be determined largely by the nearest dominant conductor but its statistical significance is likely to suffer seriously due to the mutual contamination of variations from isolated conductors.
3. If the anomalous field variations are determined by current channelling (e.g. SAB), the dependence of the intensity of induced currents on the polarization of source field is lost. The current channelling effect may contribute to the statistical evaluation of the transfer functions in an unknown manner.

Within these statistical constraints, only the most persistent features are considered for further discussion and modelling. The most significant features of the induction arrows (Fig. 3) and their spatial characteristics (Fig. 6) are:

1. The magnitudes of the real induction arrows increase gradually as one approaches the MFT from the north. After attaining a maximum in the vicinity of the MFT, the magnitude of the arrows fall off sharply to the south of the MFT. This suggests that the MFT represents a boundary of high electrical conductivity contrast, with a region of high electrical conductivity south of it.
2. At the long periods, the real and quadrature arrows are parallel to a large extent (e.g. see arrows for 60 minutes in Fig. 3), indicating that the induction response is related to a structure mostly 2-D in character (BANKS and OTTEY, 1974). This inference is largely corroborated by the frequency characteristics of the quadrature arrows. Examining the induction arrows of the present phase-I data, REDDY and ARORA (1992a) noted that the direction of quadrature arrows flips over by 180° around the period range of 30–40 minutes. The magnitude of the quadrature arrows in this period range is near-zero (see pattern in Fig. 3 for 39 minutes), whereas real arrows stabilize to a maximum magnitude around the period of 50 minutes and above. Following ROKITYANSKI (1982) and CHEN and FUNG (1985), these features were interpreted to indicate that the characteristic period which maximizes induction response in the involved conductor is around 40–50 minute period interval. In view of this, the model calculations and their comparison, as discussed in the sections that follow, are confined to periods of 39 and 60 minutes.

4. Initial Model Considerations

The thick pile of sediments in the IGP, overlies the underthrusting, low-dipping Indian plate, and is thickest in the vicinity of the MFT; such sediments provide an attractive seat for the concentration of induced currents. A number of deep bore-holes in the IGP indicate resistivity of the order of 5–15 Ωm for the sediments, and the maximum thickness does not exceed 4–5 km along the study sector (RAIVERMAN *et al.*, 1983). The initial 2-D geoelectrical model developed to account for the observed EM response included only these sediments resting on layered earth model (Fig. 4 excluding the mid-crustal conducting layer). The test calculations shown in Fig. 5a, reveal that within the constraints available on the thickness and resistivity, the response is weak compared to the observed response. However, in agreement with observed features, the peak value is registered near the MFT and falls off rather more rapidly to the SW than to the NE.

The simple 2-D block model developed earlier by REDDY and ARORA (1992a) to account for the regional scale anomaly with the peak response around MFT, required a very high conductance (2000 S) for the IGP block. Reddy and Arora suggested that the sediments in the IGP can provide only a very small fraction of the estimated conductance, and envisaged that the major source of the observed induction anomaly was deep seated, perhaps in the underthrusting Indian plate.

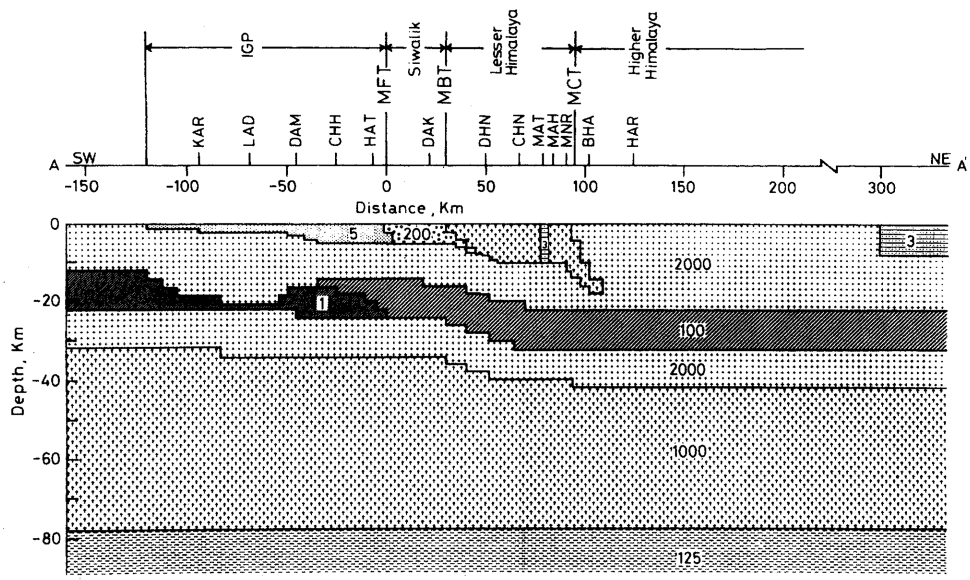

Fig. 4. Two-dimensional electrical resistivity model along the profile AA' (Fig. 2) which gives best fit to the observed EM response. Resistivities are in Ωm.

5. Updated 2-D Geoelectrical Model

The MV and magnetotelluric (MT) survey carried out across the several subduction/collision zones have revealed that a dipping high conductivity slab within the upper-middle subducting plate is a universal attribute of subduction zones (ADAM, 1980; KURTZ *et al.*, 1986; JONES, 1992). In addition to the well known Carpathian conductivity anomaly, rooted in the Carpathian mountains of eastern Europe (CERV *et al.*, 1987), more recent examples of a conducting layer overlying a subducted plate have been mapped over the Juan-de-Fuca plate (KURTZ *et al.*, 1986; EMSLAB, 1988), and the Northern Island region of the New Zealand, where the Pacific plate is being subducted beneath the Australian plate (INGHAM, 1988). Using a laboratory anologue model, DOSSO and NIENABER (1986) and DOSSO *et al.* (1989) have studied the behavior of induction anomalies associated with dipping conducting slab, simulating a subduction zone. Gross similarity of the observed induction features with that obtained in association with the above scaled anologue model, facilitates to develop a more complex 2-D electrical model, including a conducting layer in the underthrusting Indian lithosphere.

The 2-D electrical resistivity model which gives best fit to the observed response is shown in Fig. 4. The EM response of this model was calculated using numerical formulation and computer program developed by Cerv and Pek (personal communication) for a traverse AA' (see Fig. 2 for location). The comparison of observed and calculated responses at two periods is shown in Fig. 6. The model includes the surface features of the IGP, Siwaliks, Lesser Himalaya and the Higher Himalaya, with significant lateral contrasts of resistivity constraint by their lithological character. In the model developed, the sedimentary sequence in the IGP is an important surface conductive feature. The induction in the IGP basin, which from geophysical and electrical well-log data is assigned a thickness of 5 km at the MFT and resistivity of 5 Ωm, is significant, but as noted in earlier section, its response is far below the observed magnitude (Fig. 5a).

The most important feature of the model is a conducting slab, approximately 10 km thick,

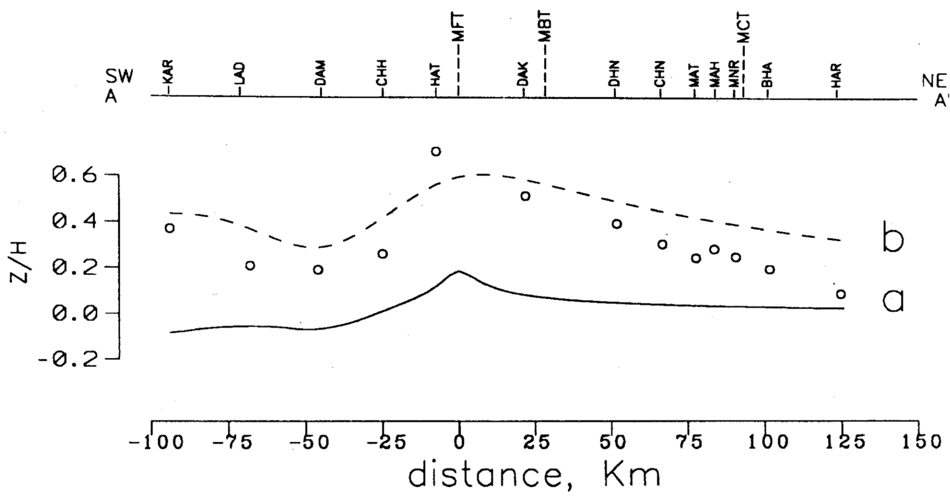

Fig. 5. Calculated induction response of the model simulating only (a) sedimentary sequence in the Indo-Gangetic plain (b) the mid-crustal conductor of 1 Ωm included in a layered earth model, shown in Fig. 4. Open circles indicate the observed response for 60 minute period.

embedded in the crust. The layer is modelled to underthrust along with the Indian plate near the Himalayan frontal belt. In Fig. 5b, we have also shown separately the characteristics of the response caused by the highly conducting slab at mid-crustal layer. Many of the spatial characteristics and magnitude of the observed pattern may be accounted for by a highly mid-crustal conductive layer embedded in the underthrusting Indian lithosphere (Fig. 5b). This crustal layer, located at an average depth of 12 km beneath the IGP, has very low resistivity, of the order of 1 Ωm. Further north of the MFT, the resistivity of this crustal layer increases to about 100 Ωm. The upper surface of the conducting layer south of MFT is found to undulate, with two clear humps, the first located close to the southern limit of the IGP and the second just south of the MFT beneath the IGP.

A narrow and shallow high conductivity body is located just south of the MCT, embedded in the Lesser Himalaya, to account for the small scale anomaly centered around MAT. And a block 8 km thick and resistivity 3 Ωm, placed at about 300 km NE of the MFT, simulates the conducting sedimentary basin associated with Indo-Tsongpo Suture Zone (THAKUR, 1981). This block is not adequately constrained by the present modelling but its inclusion facilitates to account for the spatial behaviour of the observed response north of the MCT without introducing any lateral change in the under-thrusted slab beneath the Himalaya.

6. Tectonic Interpretations

The anomalous character of the crust beneath this part of the IGP has also been inferred by CHUN (1986) from the shear wave velocity structure. Approximating the 40 km thick crust into 4 layers, CHUN (1986) showed that, between the depth of 10–40 km, the velocity in the western IGP is consistently higher than that commonly observed in the continental shield region. The velocity in the 10–20 km depth range is 3.80 km/s, a value normally associated with basaltic or gabbroic rocks and typically found in the continental lower crust. Modelled as a single layer, the lower crust from 20–40 km has an estimated velocity as high as 3.98 km/s. This characteristic velocity model led CHUN (1986) to suggest that crustal structure beneath the IGP is a strong

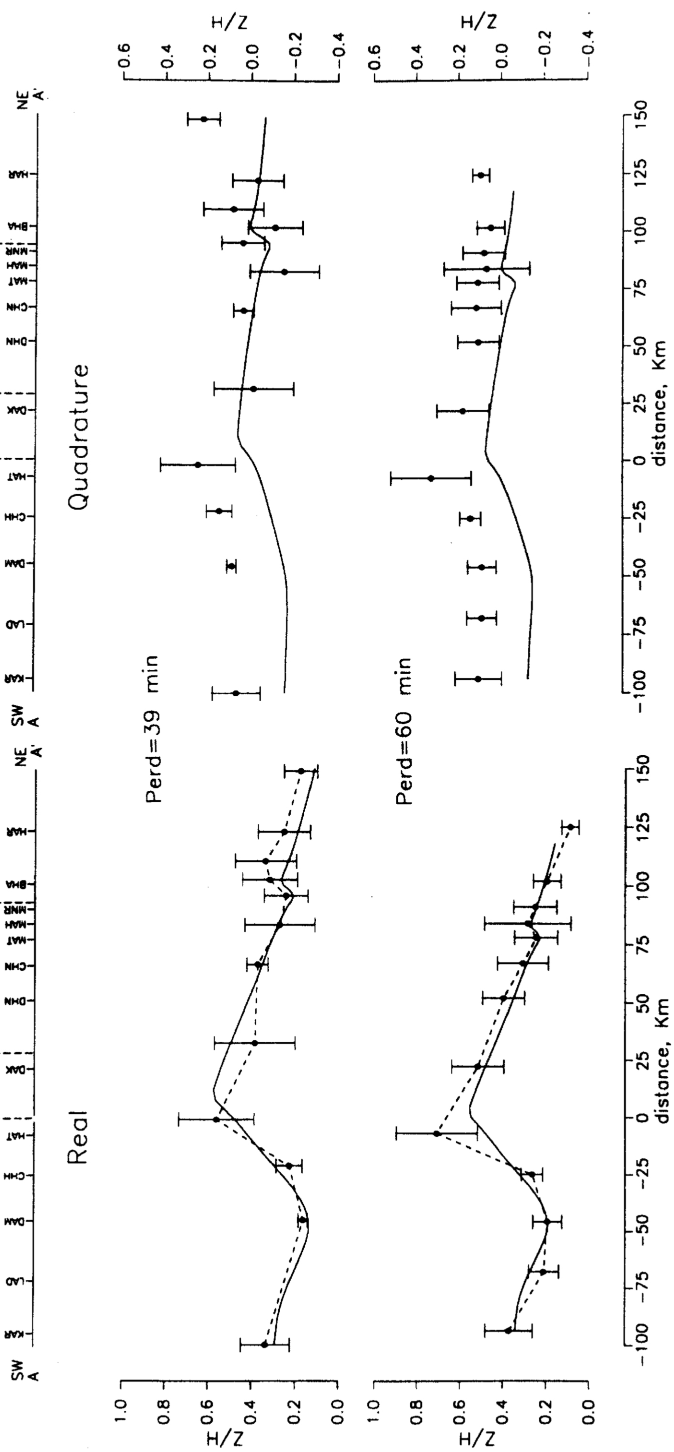

Fig. 6. Comparison of calculated EM response for the full 2-D model shown in Fig. 4 with observed in-phase and quadrature response (dashed lines). Vertical bars denote 1 sd error associated with observed response at respective sites.

reminiscent of certain oceanic plateaus. The anomalous crustal conducting layer envisaged in the geoelectrical model corresponds to the layer between 10–20 km.

It is also interesting to note that the top of the modelled conducting layer appears to correlate with a planar zone along which the foci of medium size earthquakes are located (NI and BARAZANGI, 1984). These authors have observed that foci of most moderate earthquakes with epicenters south of the MCT are aligned along a linear plane, at about 10–20 km depth, with an apparent northward dip of about 15°. This planar zone also coincides with the Basement Thrust Fault (BTF) separating the Indian plate from the overriding sedimentary wedge of the Lesser Himalaya (SEEBER *et al.*, 1981). Furthermore, the observation that micro earthquake activity in the frontal folded belt and Lesser Himalaya is confined to the upper 10–15 km of the Indian plate (KHATTRI, 1990), suggests that this lower limiting boundary of seismic activity, coinciding with the planar surface and the BTF, marks the brittle-to-ductile transition zone, produced by the effect of both temperature and pressure. It is possible that the temperature and pressure conditions may initiate metamorphic dehydration reaction, leading to the release of fluids (FYFE *et al.*, 1978). The resulting fluids may provide an effective mechanism for the enhanced conductivity in the mid-crust, beneath the IGP. HYNDMAN (1988), JONES (1987) and several others have discussed the mechanism of fluid generation, their propagation and trapping beneath the impermeable cover as a source of crustal conductor. During the continuing underthrusting of this fluid filled layer, the fluids may progressively be squeezed out at greater depth, resulting in the decrease of conductivity, as suggested by the geoelectric model in Fig. 4.

It may be possible to invoke other mechanism for enhanced conductivity, e.g. rocks bearing precipitated wet graphite films (FROST *et al.*, 1989; JODICKE, 1992) or blocks of serpentine-rich basalt (STESKY and BRACE, 1973). So far no geological evidence is available to indicate the presence of serpentine-rich basalt in Himalaya collision zone. It seems unlikely that continuity of graphite film coating at mineral grains would be retained in such a tectonically active zone to provide effective mechanism for enhanced conductivity (GOUGH, 1992).

The narrow conducting belt of 3 Ωm placed little south of the MCT is introduced to simulate the cause of geomagnetic variation anomaly between stations MAT and MAH. The correlation of this conductivity body, visualized as a near surface fracture zone, with gravity (QUERESHY *et al.*, 1974) and a well defined belt of high seismicity (GAUR *et al.*, 1985) has already been discussed in REDDY and ARORA (1992a, 1992b). The third surface feature, which is incorporated primarily based on exposed geological section, is a block of 8 km thick sediments with 3 Ωm resistivity on the NE corner of the profile (Fig. 4). This block provides marginal improvement in the fit north of the MCT. Though this block is not constrained by the present study, a recent magnetometer profile along the Nepal border, east of present profile and extending far north, indicates a high conducting block towards the Higher Himalaya. The induction arrows at the northern sites of that profile point northward, despite high conductive sediments in the IGP (Arora, unpublished work).

7. Summary

This paper presents the quantitative interpretations of EM induction response along the Ganga-Yamuna valley of the Frontal Himalaya. The main feature of the model is a conducting layer between 10–20 km depth range beneath the IGP. Shear wave velocity structure corroborates with an anomalous character of the crust in this depth range. This layer, with its undulating top, bends down to underthrust at the MFT and becomes less conducting. Other important surface features are (i) the sediments in IGP have maximum thickness of 5 km at the MFT and resistivity 5 Ωm, (ii) a 10 km wide conductive zone with its top surface at the depth of 2–3 km and resistivity 3 Ωm is indicated in the vicinity of MAT, south of MCT and (iii) a poorly constrained 8 km thick block with resistivity 3 Ωm somewhere in the Higher Himalaya.

Due to large radii of confidence circles, the model fitting is attempted only at two periods. It will be useful to use robust methods to estimate transfer functions, so as to reduce the errors and improve the model fit, for a wide period range. MT studies may resolve clearly the narrow conductor south of MCT and map the undulations in the conducting layer.

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